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W. G. Harper and J. G. D. Beimers

(Meteorological Office)

AIR MINISTRY

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The movement of precipitation belts as observed by radar

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Summary

The movement of 103 belts of precipitation over Southeast England, mostly associated with cold fronts and cold occlusions, have been measured from radar records and compared with upper winds at each 50 mb level from 950 to 500 mb.

A correlation in excess of 0.9 is found with the mean winds across the belts at the 700 mb level. Even at 650 and 750 mb the correlations are significantly lower, while at 950 mb (roughly the level of the gradient wind above the friction layer) the correlation is little more than 0.6. The mean of the wind components at 700 mb is in close agreement with the speed of the belts.

No significant variation in correlation level was found despite subdivision of the material either (a) on the basis of frontal types, or (b) on the basis of the height ranges of observed echo.

Strong support is found for the forecasting rule that cold fronts and cold occlusions move at a speed that is equal to the average component of the wind across the frontal surface at the 700 mb level.

A similar comparison has not been possible in the case of warm fronts because of the absence of well-defined edges of echo in them.

1. Introduction

In forecasting the movement of fronts the forecaster usually moves surface fronts on with the geostrophic wind scale, conveniently obtaining the component of the geostrophic wind normal to the front by laying the scale along the front of the surface chart. The rules he employs are largely empirical, but in general warm fronts are moved on at about 70 per cent of the speed of the geostrophic wind, cold fronts at between 80 and 100 per cent of the geostrophic wind or even more, allowance being made where possible for isallobaric effects and for curvature of the isobars (cf. Petterssen's (1) forecasting rules). The method is not entirely satisfactory, and occasional serious errors occur.

Ligda, (2) however, in America has compared the movement of small precipitation areas as observed by radar with winds scaled from upper air charts at the three levels 850, 700 and 500 mb, and found that the correlation in both speed and direction was better at 700 mb than at either of the other levels. The present paper attempts a more detailed comparison in the case of belts of precipitation.

2. Method adopted

Belts of precipitation are frequently observed on radar to have clearly defined edges of echo. Their direction and speed of movement can be rapidly and accurately determined from the PPI display over the limited area observed.

/Many

Many of these belts are identifiable with the passage of fronts. A clear distinction must be drawn here between the direction and speed of movement of the belt (which is measured perpendicular to its length), and the movement of the individual echoes of which it is composed, for these will normally have a component of motion along the belt which may or may not be obvious from radar. On some occasions there may also be a continuous process of development and dissipation, precipitation forming at one side of a belt, moving through and dissipating at the other, as in orographic rainfall. The present observations were taken over Southeast England, where orographic effects are negligible, and it is reasonable to assume that the belt movement as measured from radar was that of its associated front.

Reference has been made to the limited area of the normal radar display, and it is obvious that a single radar station cannot measure movement at widely spaced points along a frontal belt; but for the present study radar scores heavily in being able to define a movement accurately at one point in a belt from observations covering perhaps half an hour. In contrast, even a close network of weather reports allows considerable latitude in placing fronts, and their movement is often hard to define from synoptic charts, especially when they are slow-moving.

Comparison has been made with components of measured values of wind from the British radar-wind network. This had two main advantages over the use of geostrophic winds measured from upper air charts, namely that radar winds were available (a) every 6 hr as against the 12-hr spacing of the upper air charts, and (b) at each 50-mb level against upper air charts at 700 and 500 mb only.

3. Nature of radar material

Photographic records taken at East Hill on a 500-Kw 10-cm plan-position radar in the five-year period 1947-52 were found to include 103 belts of precipitation whose movement could be clearly defined. The average duration of the measurements on these belts was 67 minutes. They were usually recorded for longer, but outside the period of measurement were more ill-defined.

51 of the belts (50 per cent) could be identified with the passage of cold fronts shown on the Daily Weather Report, or were reasonable extrapolations of such fronts. 31 (30 per cent) could be identified similarly with the passage of occlusions. In the remaining 21 cases (20 per cent) no fronts were shown in the Daily Weather Report, and the precipitation consisted mainly of ordered collections of showers in a persistent belt. Some of these may well have been associated with minor cold fronts not regarded as essential to the synoptic analysis, and in any case no sound reason was seen for excluding them.

Measurements have not been possible on warm fronts as the radar echoes from warm-front precipitation are usually very diffuse, and no persistent edge of echo can be defined.

4. Analysis of radar material

Isochrones of a clearly-defined edge of echo were drawn for each belt of precipitation by projection of the 35-mm plan-position photographs. Slight adjustment of magnification was usually necessary from frame to frame to allow for variations in the voltage of the mains supply. No single adjustment of magnification in the projection process can eliminate a slight non-uniformity in the range scale across the display. This is inherent in any cathode-ray tube presentation. The residual error can be greatly reduced however by scaling off echo movements against their own sections of the radial range scale, and is negligible for the present purpose.

An actual plotting is shown at Fig. 1. This is of precipitation associated with a well-defined but weak cold-front passage, selected because it has enabled the echo pattern at each time to be shown. Observations in this case covered a period of 80 min, and included seven positions of the trailing edge. It can be seen that the precipitation belt is nowhere more than 3 mi in width and would probably not have given more than 10 min of rain in passing.

/A

A point that is clearly shown in Fig. 1 is the difficulty in following individual echo sequences even in as clearly defined a belt as this. The general impression of the individual movement is clear, e.g. CD in Fig. 1, but for very few could a direction and speed be given with confidence. In any case there was often a broader belt of continuous precipitation in which identification of individual echoes was impossible.

The movement of the belts was measured perpendicular to the echo-edge, e.g. along AB in Fig. 1. A single value for the speed of movement was determined graphically by plotting the intercepts measured along AB against time, and taking the slope of the mean line. This gave equal weight to each plotting, and minimized the effect of local irregularities. It might be claimed that the placing of the line AB is rather arbitrary, but the variability of measured speed due to this cause is usually less than the probable error in the measured winds. Not all the belts were as smooth as this one, and in general some degree of smoothing of slight protuberances and indentations in the echo edge has been necessary.

5. Comparison with upper winds

The advantages of comparison with measured wind components over values scaled from upper-air charts are given in para. 2. Two radar-wind ascents were used for each belt, one to represent the winds ahead, the other the winds behind the belt, the choice being affected by the orientation of the belt. Whenever possible one ascent was chosen downwind and one upwind from the area in which the belt movement was measured, but it was not possible to hold rigorously to this because of the more limited choice of ascents to the south and east of East Hill. On average the soundings used were 40 mi ahead and 100 mi behind the belts, and as close as possible in time. Those used for the belt shown in Fig. 1 were Liverpool and Larkhill at 0800 G.M.T.

6. Results

The results are presented graphically. The upper curves of Fig. 2 are the correlations with the mean wind components for the full 103 belts and with the wind components ahead of and behind the belts, while the wind components themselves are plotted against the scale of knots at the right-hand edge of the diagram (lower curves), with the mean speed of the belts indicated for comparison.

The striking features are

(a) that the correlations have a well-defined maximum of high significance at 700 mb

(b) that the correlations are much lower at 950 mb (which roughly represents the gradient wind at 2,000 ft) and at 500 mb

It is of interest to compare this with the correlations found by Ligda (2) for the movement of small precipitation areas. He compared both the direction and speed of movement of 90 storms with geostrophic winds scaled from upper air charts at the three levels 850, 700 and 500 mb, and obtained the following correlations:-

Pressure, mb	850	700	500
Direction	0.73	0.96	0.87
Speed	0.49	0.81	0.58

The variation in speed correlation is in excellent agreement with the form of the curve of Fig. 2

(c) that the best level of agreement of mean belt speed with mean wind components is also close to 700 mb

/(d)

(d) that the correlations are higher for the mean winds at all levels than for those ahead of or behind the belts

(e) that the mean wind components behind the belts are stronger than those ahead at all levels.

Fig. 3 is a scatter diagram of the belt movements at the 700 mb level, with belt speed plotted against the mean of the wind components. The mean belt speed was 19.3 kt, and the extreme speed is seen to be 45 kt. An explanation of the negative and zero values is desirable. The direction of movement of the belt on the radar display was always taken as positive. If the mean wind component turned out negative, this of course adversely affected the correlation at the level concerned. There are two such cases at 700 mb, but the negative components are small. In the three cases of zero belt speed, although there was no detectable movement of the belt where the echo edge was well-defined, there was a small movement one way or the other in the less well-defined parts of the display, and this was taken as positive. A wind component opposed to it was counted negative.

To allay any suspicion that features of Fig. 2 may have been fortuitous, correlations and wind components have been evaluated separately for the 51 cold fronts and for the 31 occlusions. These are presented in Fig. 4 and 5. The main features to which attention has already been drawn are present in both. There is the same rapid improvement in correlation from 950 to 800 mb, and the highest correlation in both is at the 700 mb level, although for the cold fronts the correlation remains high between 750 and 550 mb. The best agreement between the actual values of belt-movement and wind component lies within 50 mb of the 700 mb level in each case.

For the sake of completeness Fig. 6 presents curves derived from the 21 belts of showers. Even here the same broad features exist, but there is no well-defined maximum in the correlation curves. The fairly uniform correlation from 900 to 600 mb (curve C) may be due to the fact that occasions suitable for convective development are usually characterised by small variations of wind with height, and it is probable that the winds themselves are more highly correlated than usual. The rapid fall-off in correlation from 0.82 at 550 mb to 0.51 at 500 mb in curve A appeared suspicious, and the individual wind values were closely examined. It was found that on one ascent a completely different wind regime had set in above 550 mb, associated with a pronounced upper trough. From 295 deg/29 kt at 550 mb the wind backed to 240 deg/64 kt at 500 mb. This was clearly unrelated to the shower development in the northwesterly airstream. Exclusion of this belt would have raised the correlation coefficient for the remaining 20 shower belts from 0.51 to 0.69 at 500 mb while leaving that at 550 mb practically unchanged. This draws attention to the inadequacy of these 21 cases as a statistical sample. The effect of excluding this one belt from the main correlation for the 103 belts is however almost negligible.

The correlation coefficients and wind components are given as a table (Table 1).

7. Separation into height ranges of echo top

A further test of the validity of the 700 mb correlation has been applied by separating the material into ranges on the basis of the heights of the observed radar echo tops. These classes have been correlated separately. Range-height information was available for 77 of the 82 belts associated with cold fronts and occlusions. In most cases precipitation was continuous from echo top level to the ground, either as diffuse echo, or with some column structure; in a few cases the echo top was associated with an upper layer-type echo which may or may not have been related to the rain reaching the ground. No attempt has been made to discriminate between these types.

/The

The heights of maximum echo top have been analysed into various height ranges in Table 2. It is of interest that only 7 of the 77 belts have a maximum echo top at 10,000 ft (700 mb) or below.

Table 2. Numbers of occasions of maximum echo tops associated with cold fronts and occlusions falling in the given ranges.

Height range 10^3 ft	Cold fronts	Occlusions	Total
0 - 5	0	0	0
6 - 10	3	4	7
11 - 15	15	8	23
16 - 20	11	9	20
21 - 25	12	4	16
26 - 30	3	3	6
31 - 35	2	2	4
36 - 40	0	1	1
Total	46	31	77

There were roughly equal numbers of cases above and below 18,000 ft, and the wind components for these classes have been correlated and meaned separately to see if any variation in correlation level could be related to the radar appearance, for the 46 cold fronts (Fig. 7), for the 31 occlusions (Fig. 8), and for the whole 77 fronts (Fig. 9).

Only in the cold fronts is there any difference in level of best correlation. The 24 with echo tops above 18,000 ft have their maximum at 650 mb (0.93), while the 22 with tops below 18,000 ft have a broader maximum from 750 to 700 mb (0.94 to 0.95). The wind components at 700 mb for the former agree closely with the speed of the belts, but for the latter are almost 2 kt greater and are nearly constant from 800 to 650 mb. In both Fig. 8 and 9 the best correlations are at 700 mb, and the mean wind components are within 1 kt of the mean belt velocities. The numbers of cases in the correlations of Fig. 7 and 8 are of course rather small. The results are not very conclusive, but indicate that no variation of 'steering level' with height is deducible from radar.

8. Discussion

The wind components measured behind the belts of precipitation were on average stronger at all levels than those measured ahead of the belts (para. 6(e)). This is clearly shown in Fig. 2. It represents an inflow of air consistent with the frontal character of the belts, but an independent check of the reasonableness of the winds is desirable.

The excess of the wind component normal to a cold front surface in the cold air over that in the warm air is related to the upglide of the warm air relative to the cold. An average vertical velocity could be derived if we knew the average frontal slope, but we are not on firm ground in assuming a frontal slope. We think it preferable to assess roughly the weight of air lifted and from suitable environmental conditions to derive the average rainfall from the belt.

It is assumed that there was on average no uplift in the cold air. This is supported by Fig. 2. The wind normal to the belt in the cold air was less than the belt speed below 850 mb, and the effective excess at levels above 850 mb must have been carried downwards in order to make up the large deficit of air below 850 mb and so maintain the identity of the frontal surface. We have therefore limited the computation to the warm air ahead of the belts, and have assumed that all the overtaken air between 1,000 and 650 mb (the level at which the warm air wind component equalled the mean belt speed) must have been lifted to the higher level or have displaced an equivalent amount of air to that level, which is the same for present purposes. This lifting must occur if there is no acceleration of air parallel to the belt. The lapse of air temperature assumed for the lifting and for the environment was the saturated adiabatic through 10°C at 1,000 mb. This implies a freezing level at 800 mb and a temperature of -11°C at 650 mb, reasonable values for Southern England.

/Considering

Considering a column of air of cross-section 1 cm^2, the weight of air in any 50-mb layer will be roughly 0.05 kg. From the tephigram we find that the 50-mb layer from 950 to 900 mb will have a humidity mixing ratio for saturated air of 6.5 g/kg before lifting, but only 2.5 g/kg at 650 mb. A small part of the excess will probably be lost by evaporation in falling through cold air but as a first approximation we shall neglect this and assume that the balance of 4.0 g/kg will ultimately be made available as precipitation at the ground. This unit column contributes a quantity 'm' of water, in this case 0.20 g. We can extract values of 'm' for each 50-mb layer from the tephigram.

We see that $m(v_f - v_a)$ is the weight of water released in unit time along unit length of the belt due to the lifting of the air in this layer, where v_a is the wind component in the warm air, and v_f is the mean belt speed. But in this time the belt has moved a distance v_f, and assuming uniform precipitation in time we see that the contribution ΔR to the rainfall on unit area due to this layer is $m(v_f - v_a)/v_f$. The contributions from the various layers are given in the following table:-

Table 3. Computation of average belt rainfall.

Layer mb	m gm	$\frac{v_f - v_a}{v_f}$	ΔR mm
1,000-950	0.24	0.57	1.36
950-900	0.20	0.38	0.76
900-850	0.17	0.23	0.39
850-800	0.13	0.17	0.22
800-750	0.09	0.13	0.12
750-700	0.05	0.08	0.04
700-650	0.02	0.04	0.01
		Total	2.90

A slight extrapolation of the v_a curve has been necessary to give a value to $(v_f - v_a)$ for the 1,000 to 950 mb layer, and it is worth noticing that this layer makes the largest contribution to the rainfall total of 2.9 mm.

We assumed for simplicity that lifting took place to 650 mb, but the lifted air could not all have been disposed of at that level. Lifting must have continued into the layers just above 650 mb where $v_a > v_f$. This is supported by the echo top evidence of Table 2 which suggests that some lifting took place on average to 18,000 ft (500 mb). The computed rainfall is not in fact greatly increased by this additional lifting because of the much slower rate of change of humidity mixing ratio of saturated air with height at these levels. A computation similar to Table 3 for lifting to 500 mb gives an average belt rainfall of 4.0 mm.

Rainfall between 2.9 and 4.0 mm is very reasonable for cold-front type belts of precipitation, and this gives us added confidence in the validity of the measured wind components and in their correlation with belt speed.

The high correlation at 700 mb can only be regarded as empirical. It is not possible from this limited study to attribute it to any physical cause. It seems quite possible that fronts which give no precipitation at all also move on average with the 700 mb wind, although none were of course included in our radar studies. This might be inferred from the results of para. 7. The subdivision on the basis of height of echo tops was, one must suppose, a rough separation of the more active from the less active fronts, yet no substantial difference in correlation level was found. The extrapolation to rainless fronts is not such a great step. It must be remembered that the forecaster is often more interested in the movement of fronts because of the changes of airmass involved than with the weather along them.

/If

If the data of Fig. 2 had had submerged in them a significant number of belt speeds which correlated at levels substantially different from 700 mb an over-all correlation as high as 0.93 would surely have been impossible, and we think there is strong support from the present paper for the forecasting rule:- "Cold fronts and cold occlusions move with a speed equal to the component of the wind across the front at the 700 mb level."

9. References

1. Petterssen, S. 1940 "Weather analysis and forecasting". McGraw-Hill, New York.

2. Ligda, M.G.H. 1953 "The horizontal motion of small precipitation areas as observed by radar". Tech. Rep. No. 21, Dept. of Met., M.I.T., Cambridge, Mass.

NOTE

Some of the belts of precipitation discussed in this paper were not associated with easily identifiable fronts on the relevant synoptic charts. This should be borne in mind by the reader and the paper should be regarded as referring to belts of precipitation and not necessarily to the movement of cold fronts or occlusions.

Table 1. Correlation of upper wind components V (kt) at various pressure levels with the speed of movement of precipitation belts V'. The highest correlation in each column is underlined.

P mb		COLD FRONTS			OCCLUSIONS			SHOWER BELTS			ALL BELTS				P mb
		Winds ahead	Winds behind	Mean winds	Winds ahead	Winds behind	Mean winds	Winds ahead	Winds behind	Mean winds	Winds ahead	Winds behind	Mean winds		
950	r	.521	.553	.603	.551	.582	.599	.755	.679	.747	.599	.604	.647	r	950
	V	10.6	15.0	12.8	7.1	10.6	8.9	14.5	18.8	16.7	10.3	14.5	12.4	V	
900	r	.662	.685	.751	.543	.693	.658	.854	.773	.840	.681	.721	.754	r	900
	V	14.9	18.6	16.8	9.4	13.0	11.2	18.1	21.2	19.6	13.9	17.4	15.7	V	
850	r	.736	.804	.835	.689	.785	.791	.882	.777	.865	.769	.806	.838	r	850
	V	17.5	21.2	19.4	9.9	15.2	12.5	18.9	23.2	21.1	15.5	19.8	17.7	V	
800	r	.761	.802	.869	.764	.850	.866	.810	.781	.833	.787	.824	.864	r	800
	V	17.9	22.5	20.2	10.9	15.2	13.0	20.1	23.6	21.9	16.2	20.5	18.4	V	
750	r	.836	.824	.898	.835	.875	.910	.799	.799	.842	.839	.842	.895	r	750
	V	18.9	22.6	20.8	12.5	16.0	14.2	20.1	23.7	21.9	17.2	20.9	19.0	V	
700	r	.842	.875	.934	.899	.885	.944	.888	.804	.884	.875	.862	.928	r	700
	V	19.9	23.3	21.6	13.3	17.9	15.6	20.3	24.3	22.3	18.0	21.9	19.9	V	
650	r	.847	.869	.919	.843	.830	.880	.877	.799	.881	.862	.845	.902	r	650
	V	21.3	23.9	22.6	13.5	17.7	15.6	22.3	26.0	24.2	19.2	22.5	20.8	V	
600	r	.848	.862	.910	.817	.803	.858	.831	.733	.847	.842	.817	.884	r	600
	V	24.0	25.0	24.5	13.7	16.9	15.3	22.4	26.8	24.6	20.6	22.9	21.8	V	
550	r	.814	.823	.893	.808	.762	.858	.822	.647	.804	.825	.759	.868	r	550
	V	26.0	26.5	26.2	15.4	17.8	16.6	24.7	29.7	27.2	22.5	24.5	23.5	V	
500	r	.773	.769	.856	.805	.780	.852	.510	.583	.653	.735	.727	.814	r	500
	V	27.6	28.7	28.2	16.2	17.4	16.8	25.0	31.3	28.1	23.7	25.8	24.7	V	
V' kt		20.7			15.5			21.5			19.3				V' kt
No.		51			31			21			103				No.

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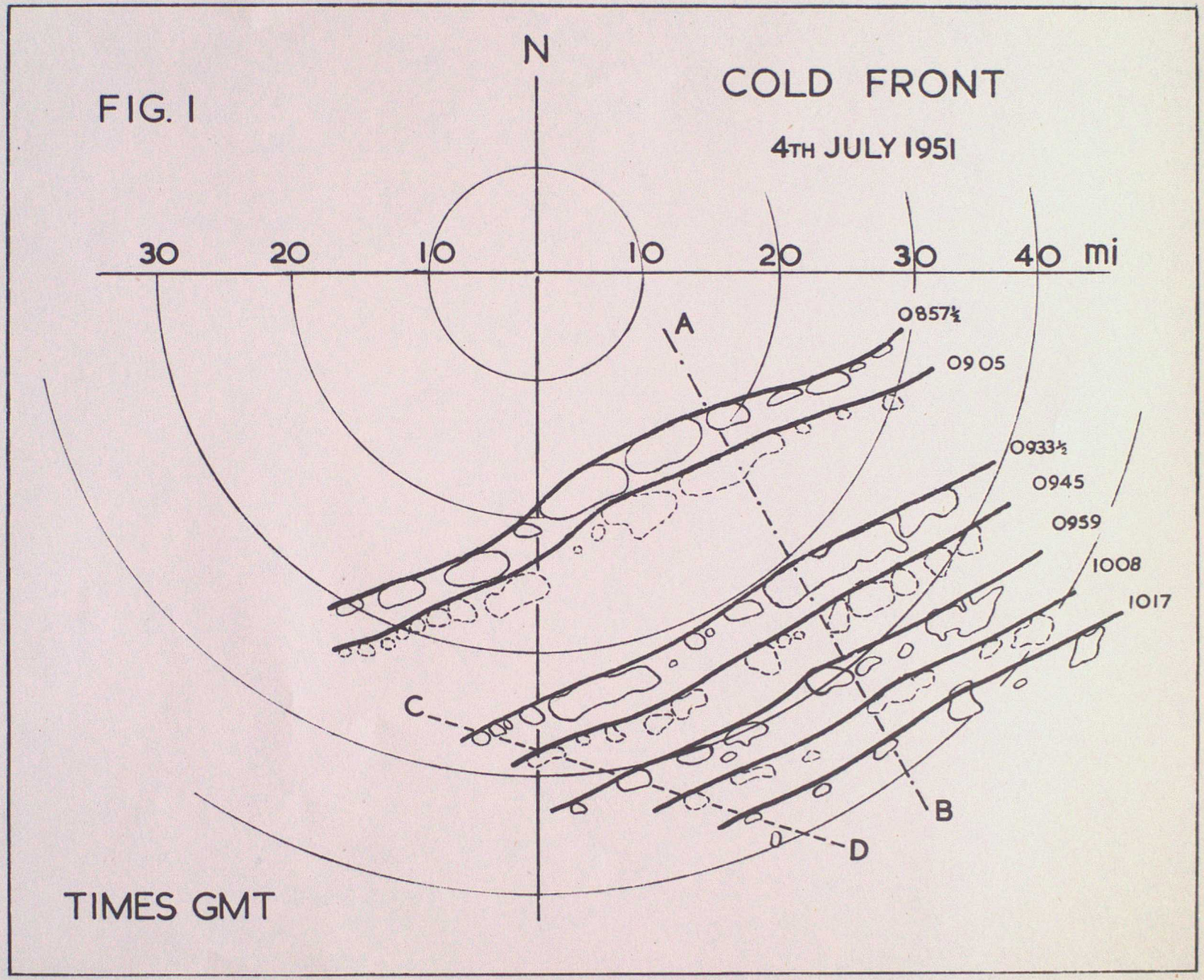
FIG. 1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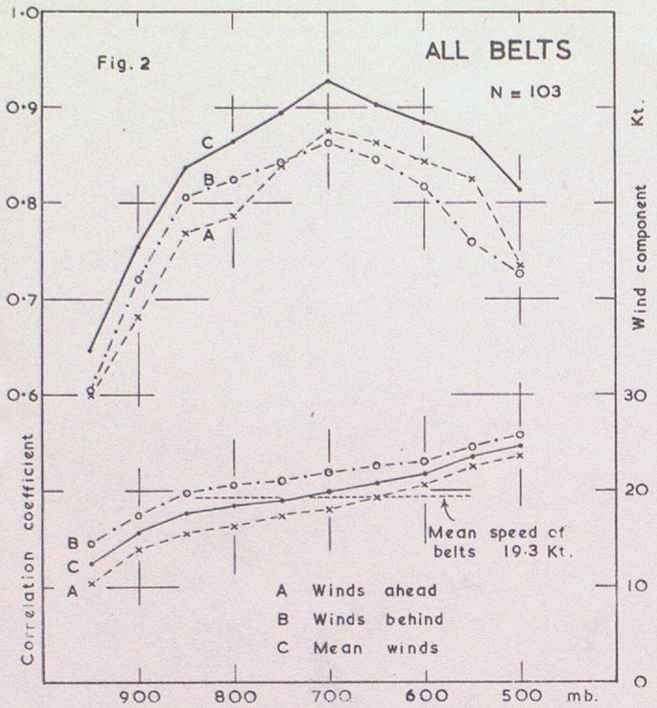

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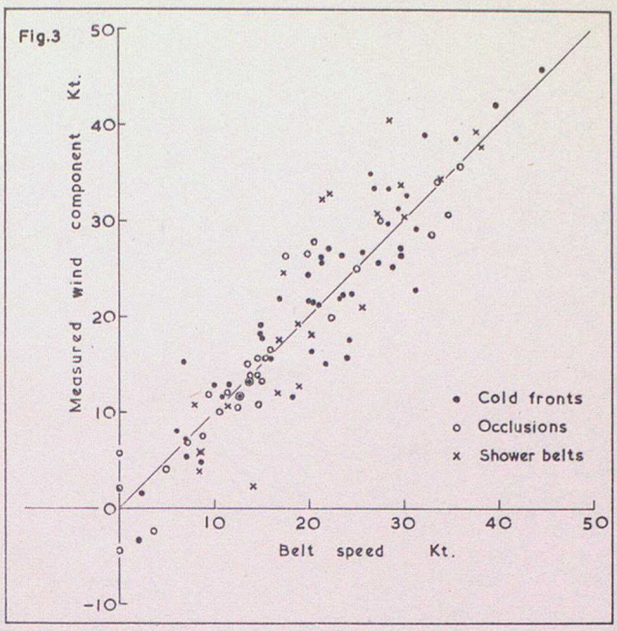
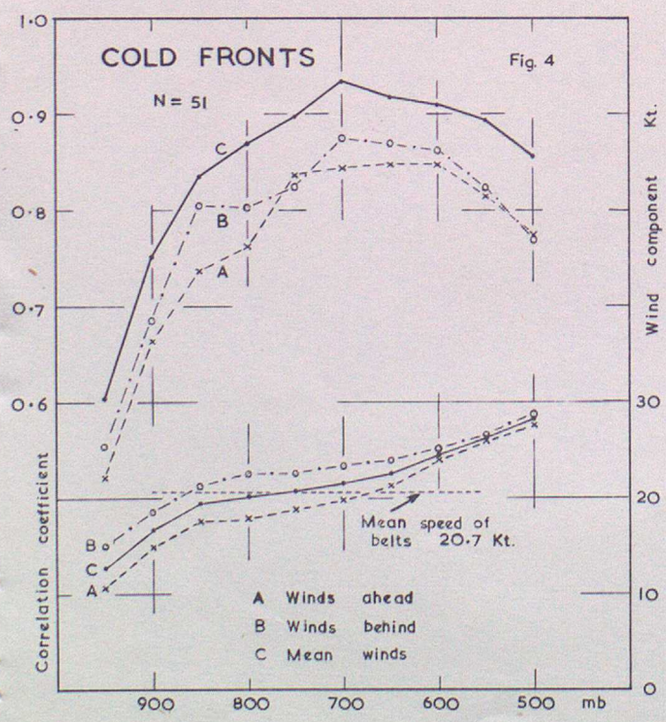
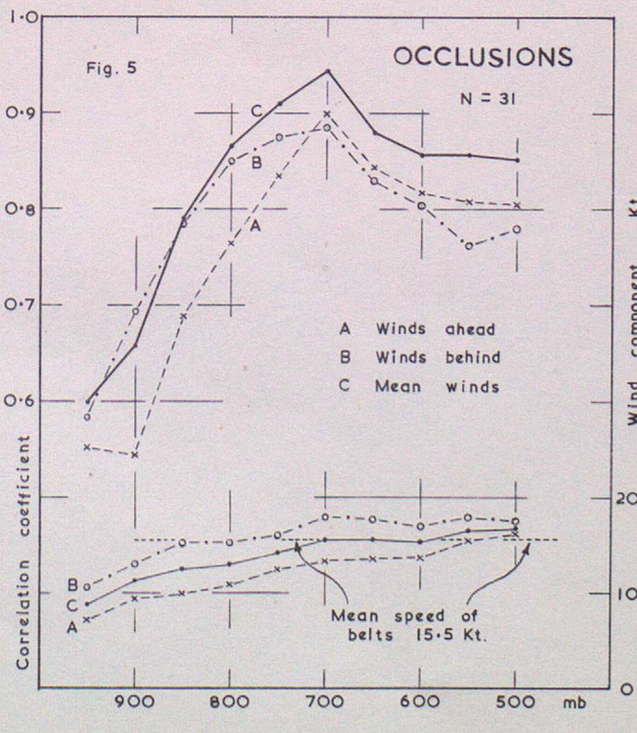


Scatter diagram of 700 mb wind components against precipitation belt speed



Correlation of movement of precipitation belts with measured upper winds



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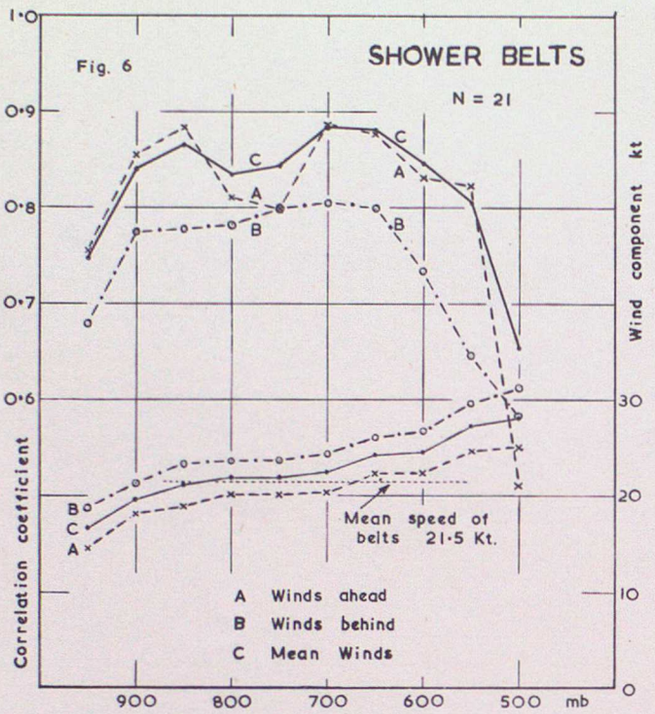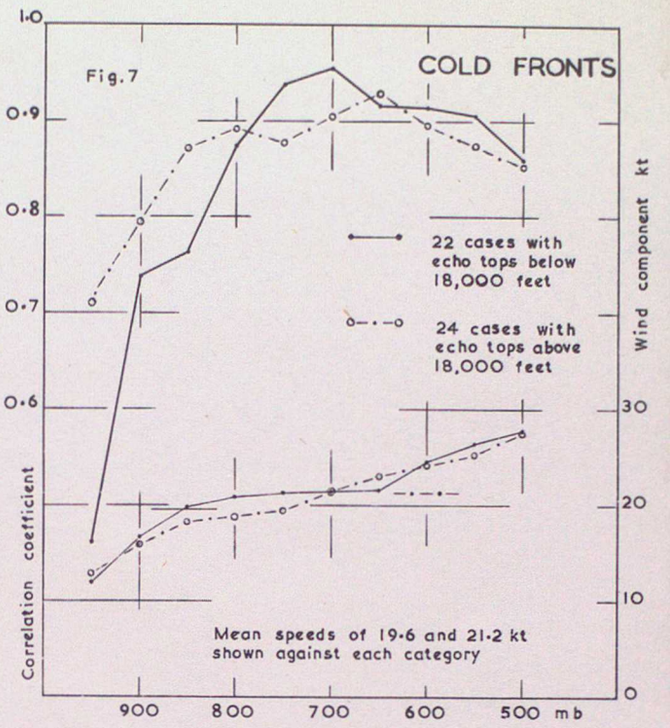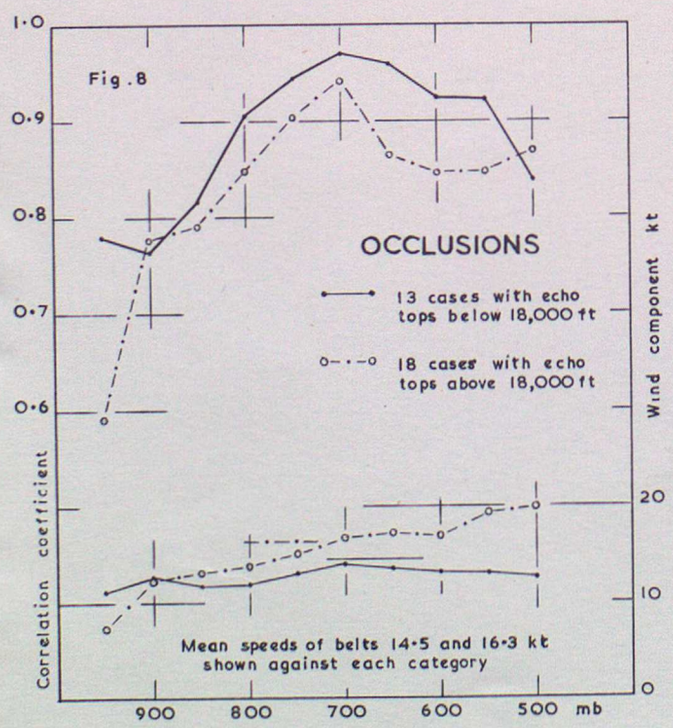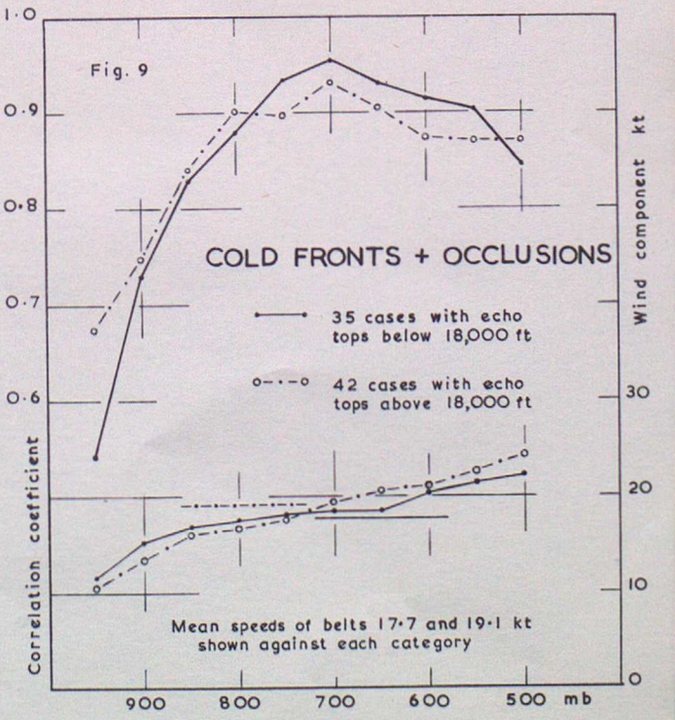
Correlation of movement of precipitation belts with measured upper winds